Toward a physics design for NDCX-II, an ion accelerator for warm dense matter and HIF target physics studies*

A. Friedman[1,5], J. J. Barnard[1,5], R. J. Briggs[2,5], R. C. Davidson[3,5], M. Dorf [3,5], A. Faltens[2,5], D. P. Grote[1,5], E. Henestroza[2,5], E. P. Lee[2,5], M. Leitner[2,5], B. G. Logan[2,5], A. B. Sefkow[3,5], W. M. Sharp[1,5], W. L. Waldron[2,5], D. R. Welch[4], and S. S. Yu[2,5]

[1] *Lawrence Livermore National Laboratory, Livermore, California, USA*
[2] *Lawrence Berkeley National Laboratory, Berkeley, California, USA*
[3] *Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA*
[4] *Voss Scientific, Albuquerque, New Mexico, USA*
[5] *Heavy Ion Fusion Science Virtual National Laboratory*

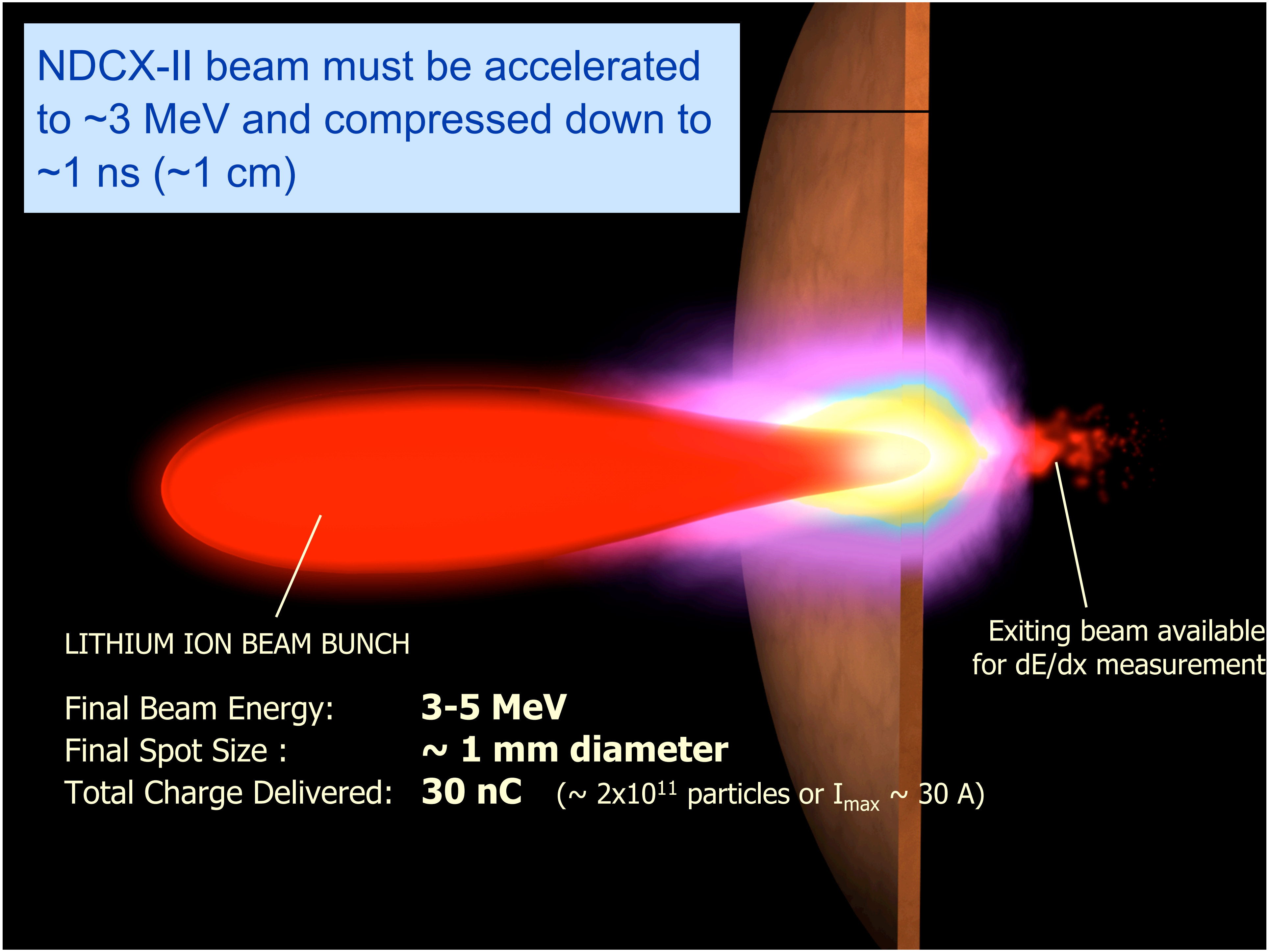
17th International Symposium on Heavy-Ion Inertial Fusion (HIF2008)
3-8 August 2008, Tokyo Institute of Technology, Tokyo, Japan

*This work was performed under the auspices of the U.S. Department of Energy by LLNL under Contract DE-AC52-07NA27344; by LBNL under Contract DE-AC02-05CH11231; and by PPPL under Contract DE-AC02-76CH03073.

Outline

- Goals and approach
- Design as developed using 1-D code
- Studies using Warp and LSP codes
- Brief comment on PLIA (Pulse Line Ion Accelerator)
- What remains to be done

Goals and approach


NDCX-II beam must be accelerated to ~3 MeV and compressed down to ~1 ns (~1 cm)
LITHIUM ION BEAM BUNCH
Exiting beam available for dE/dx measurement
Final Beam Energy: 3-5 MeV
Final Spot Size : ~ 1 mm diameter
Total Charge Delivered: 30 nC (~ 2×10^{11} particles or I_{max} ~ 30 A)

NDCX-II represents a significant upgrade over NDCX-I

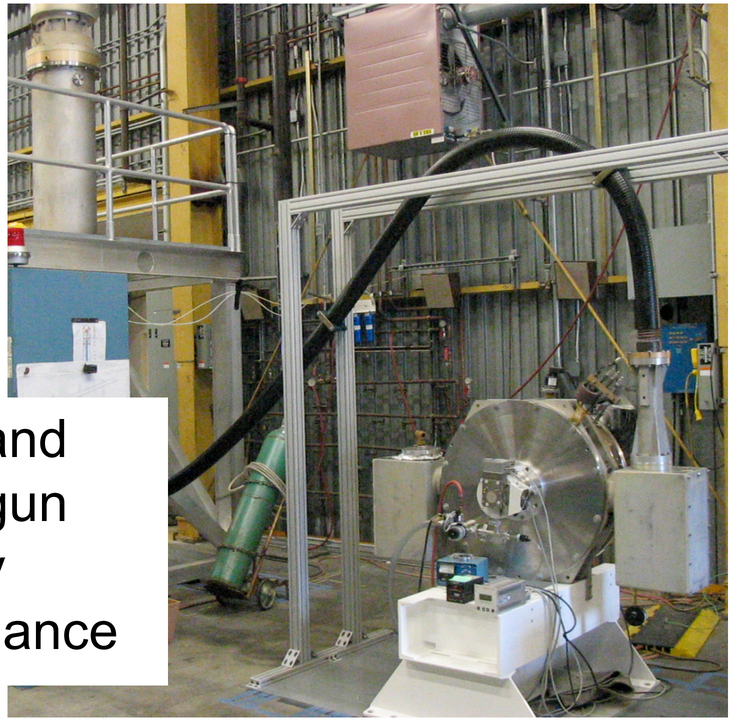
	Ion (atomic number / mass of common isotope)	Linac voltage - MV	Ion energy - MeV	Beam energy - J	Target pulse - ns	Range -microns (in ..)	Energy density 10^{11} J/m^3
NDCX-I	K^+ (19 / 39)	0.35	0.35	0.001-0.003	2-3	0.3/1.5 (in solid/ 20% Al)	0.04 to 0.06
NDCX-II	Li^{+1} (3 / 7) or Na^{+3} (11 / 23)	3.5 - 5	3.5 - 15	0.1 - 0.28	1-2 (or 5 w hydro)	7 - 4 (in solid Al)	0.25 to 1

- For initial WDM experiments: baseline is a 1-ns Li^+ pulse.
- For experiments relevant to ion direct drive: require a longer pulse with a "ramped" kinetic energy, or a double pulse.

  Glen Westenskow explored one approach to the latter.
- Possibility: Na^{+3} at 15 MeV has a shorter range than Li^+ at 5 MeV, due to the Z^2 scaling of ion deposition (per TRIM code).

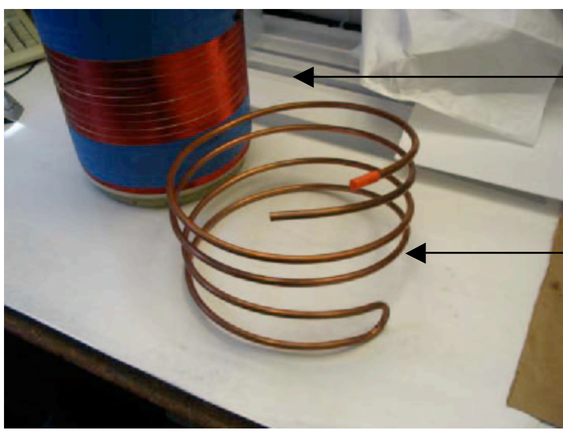
  It would require stripping on a dense plasma jet, introducing scattering; but Na may offer a higher source current density than Li.

Induction cells for NDCX-II are available from LLNL's decommissioned ATA facility



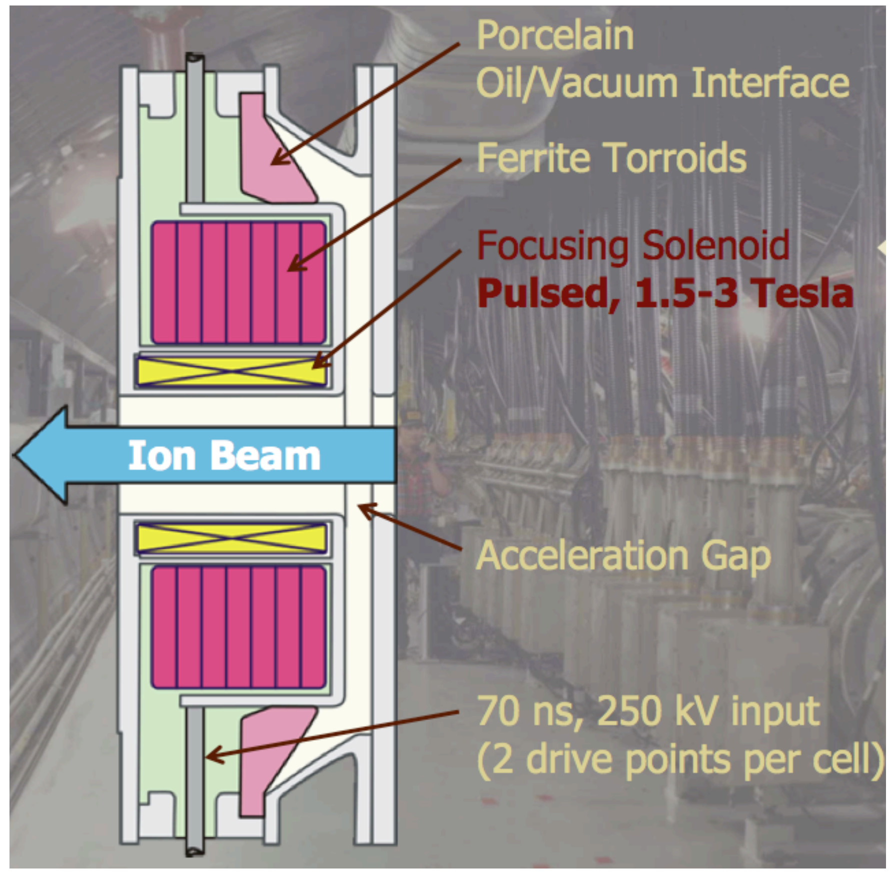
Test stand has begun to verify performance

Cells will be refurbished with stronger, pulsed solenoids

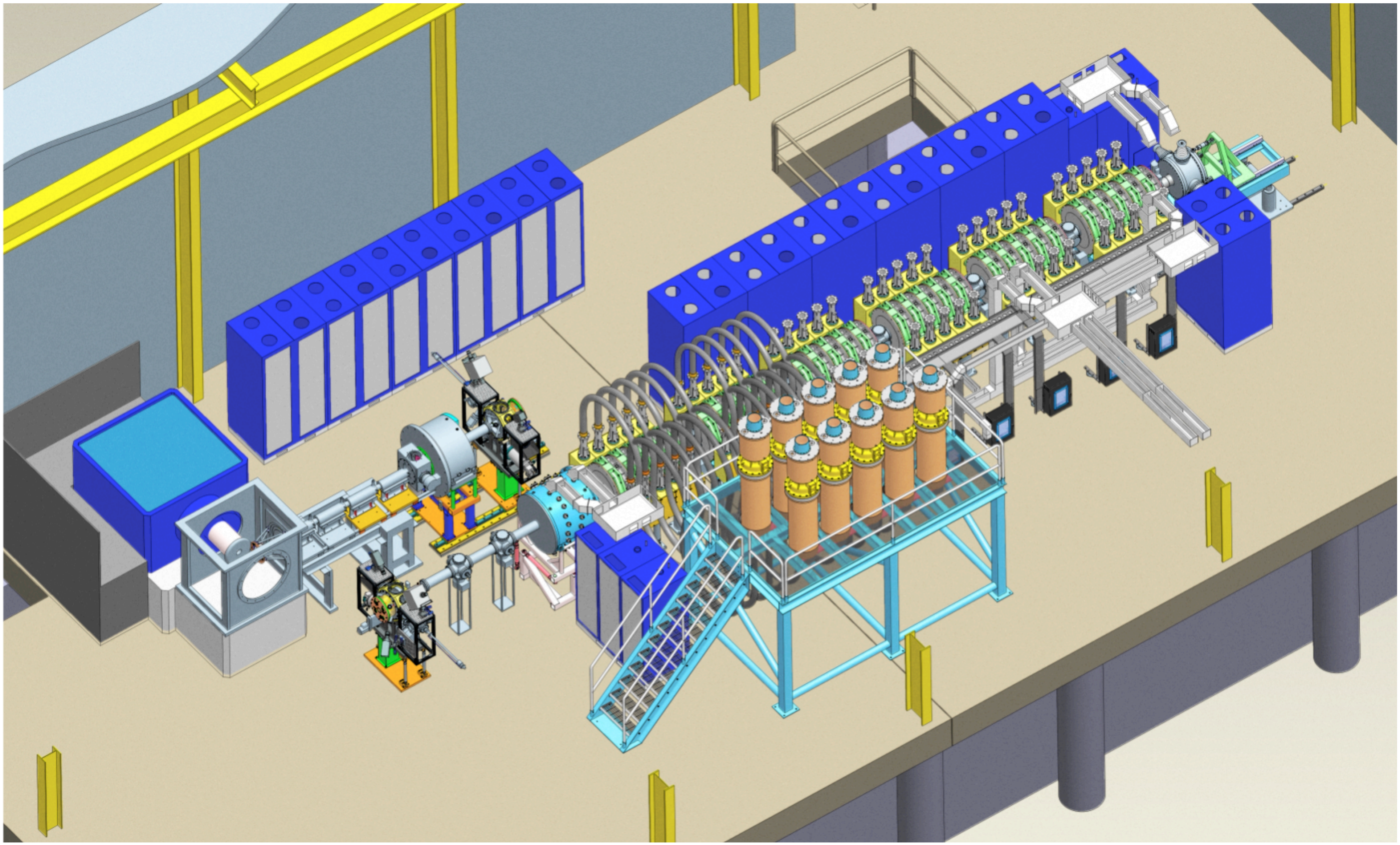


solenoid

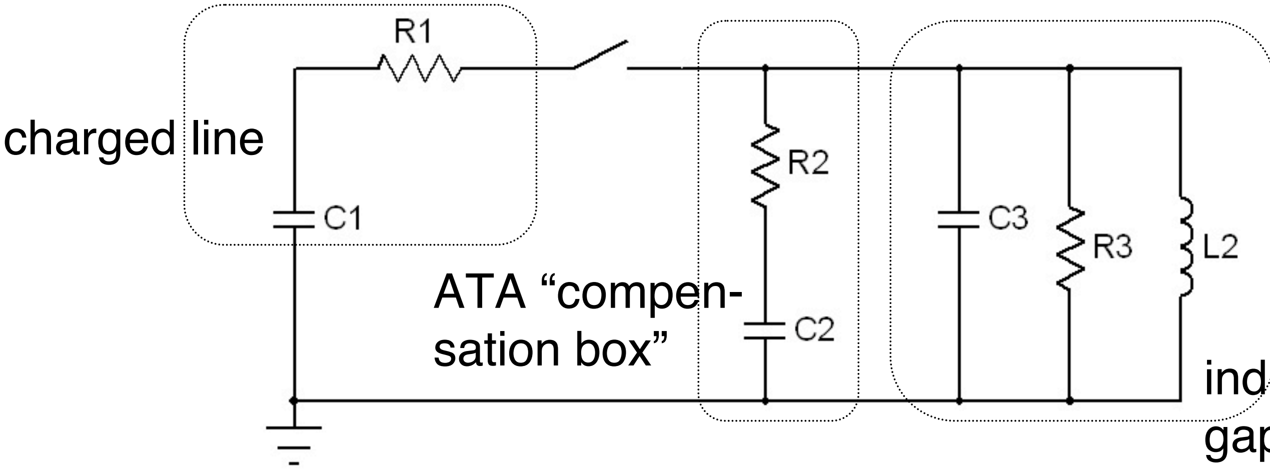
water cooling



The HIFS-VNL has sufficient ATA parts to build NDCX-II, *enabling beam-target experiments at the Bragg peak & studies of ion direct-drive for IFE*

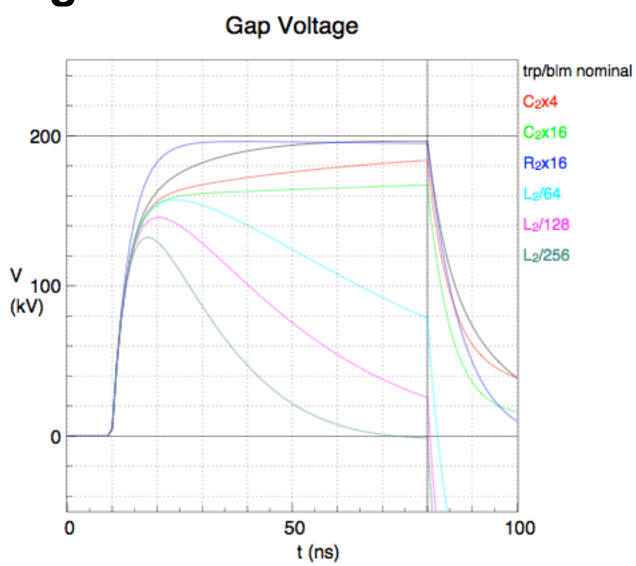


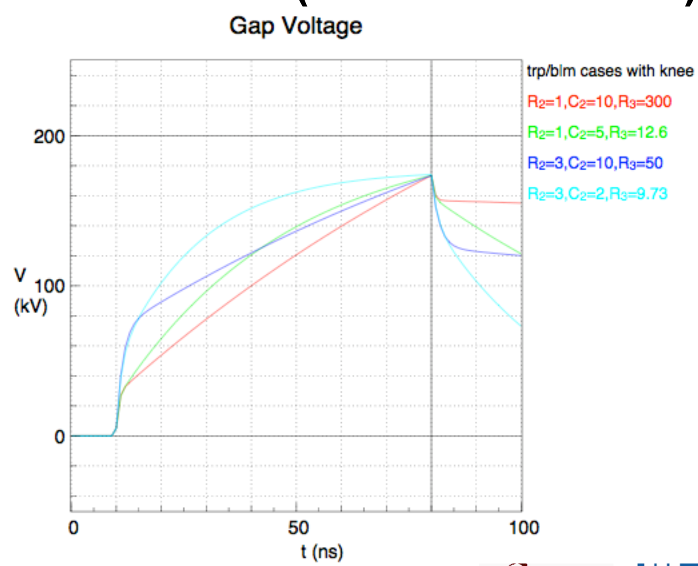
This simple circuit can generate a wide variety of shapes; other equally simple circuits offer additional waveforms



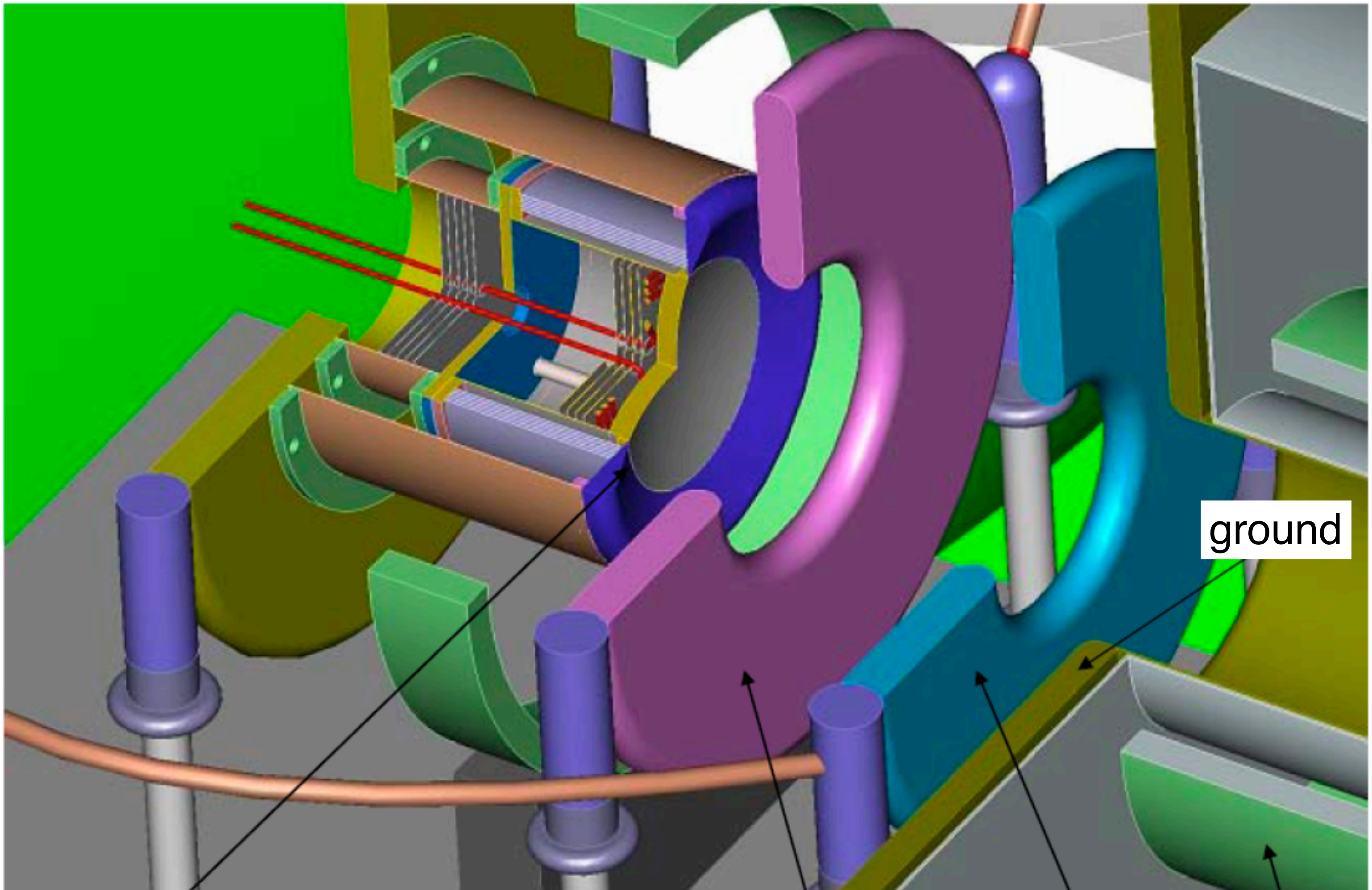
(C3 can be increased, R3 or L2 decreased, by inserting additional components across the cell)

Waveforms generated for various component values (Blumlein source):





NDCX-II uses an accel-decel injector in which the “einzel lens” effect provides transverse confinement



+102 kV pulsed source
10 mA/cm^2

+68 kV DC
extraction electrode

-170 kV DC
accel electrode

solenoid

NDCX-II must make effective use of assets (accelerating cells and Blumleins) from decommissioned ATA accelerator

Issues:

- ATA cells come with constraints:
  - 1.4 x 10^{-3} Volt-seconds in each ferromagnetic core
  - ATA Blumleins offer 200-250 kV, but only if pulse is < 70 ns
  - At front end where longer pulses are needed, use custom voltage sources; limit to ~ 100 kV for cost
- A gap must be "on" while any of the beam overlaps its extended fringe field. To shorten that field, the 6.7-cm radius of the ATA beam pipe is reduced to 4.0 cm
- Some pulses must be "shaped" to combat space charge forces
- So, need at least ~30 cells (20 w/ Blumleins + 10 w/ lower-voltage sources)

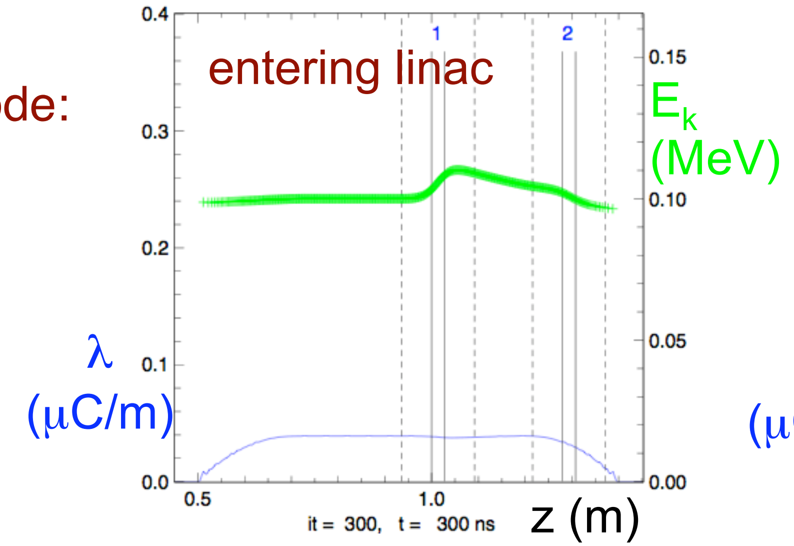
Nice developments:

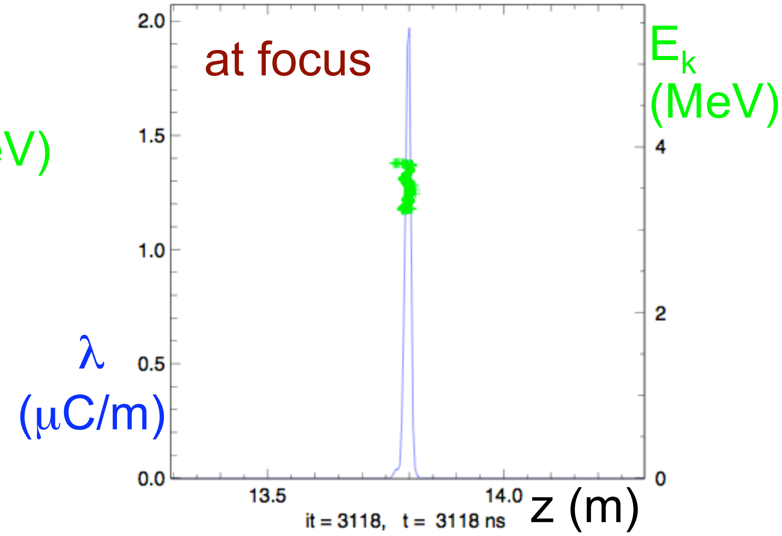
- At least 40 ATA cells are available
- The 200-kV pulses can be shaped via inexpensive passive circuits
- At higher energies, concept uses modular 5-cell "blocks"
- Induction accelerator can impart all or most of final ~8% velocity "tilt"

We are well on our way toward a physics design for NDCX-II

- Accel-decel injector produces ~ 100 keV Li^+ beam with ~ 67 mA flat-top
- Induction accelerates it to 3.5 MeV at 2 A
- The design is necessarily aggressive; 500 ns beam must be compressed to ~ 1 ns

From 1-D code:





- After neutralized drift compression, about 75% of the 30 nC beam charge passes through the focal plane in a 1-ns window, with a minimal pre-pulse.
- The current of the compressed beam (averaged over 1 ns) is 23 A, with a peak (averaged over 0.1-ns) of 32 A and an FWHM of 1 ns.
- *However, w*e're just beginning to develop the transverse dynamics & final focusing

Physics design effort relies on PIC codes

- 1-D PIC code that follows (z,v_z)
  - Poisson equation with transverse falloff (“HINJ model”) for space charge

    $g_0 = 2 \log (r_{pipe} / r_{beam0})$ $\qquad$ $k_\perp{}^2 = 4 / (g_0\, r_{beam0}{}^2)$
  - A few hundred particles
  - Models gaps as extended fringing field (Ed Lee’s expression)
  - Flat-top initial beam with parabolic ends, with parameters from a Warp run
  - “Realistic” waveforms: flat-top,“triangles” from circuit equation, and low-voltage shaped “ears” at front end
  - Interactive (Python language)
- Warp
  - 3-D and axisymmetric (r,z) models; (r,z) used so far
  - Electrostatic space charge and accelerating gap fields
  - Time-dependent space-charge-limited emission
- LSP
  - 3-D and axisymmetric (r,z) models; latter used to date
  - Fully EM or Ohm’s Law fields

Principle 1: Shorten Beam First ("non-neutral drift compression")

- Compress longitudinally before main acceleration

- Want < 70 ns transit time through gap (with fringe field) as soon as possible

  ==> can then use 200-kV pulses from ATA blumleins

- Compress carefully to minimize effects of space charge
  - Avoid space-charge forces on main flat-top of pulse at early times
  - Constant line charge ==> ear fields required only at beam ends

- Want linear velocity tilt $v_z(z) = \alpha z + \beta$
  - Ideally, uniform spacing of "beads on the string" to avoid deformation of flat-top
  - At least two gaps are required to apply such a tilt

    For zero-length gaps, two gaps can do it exactly

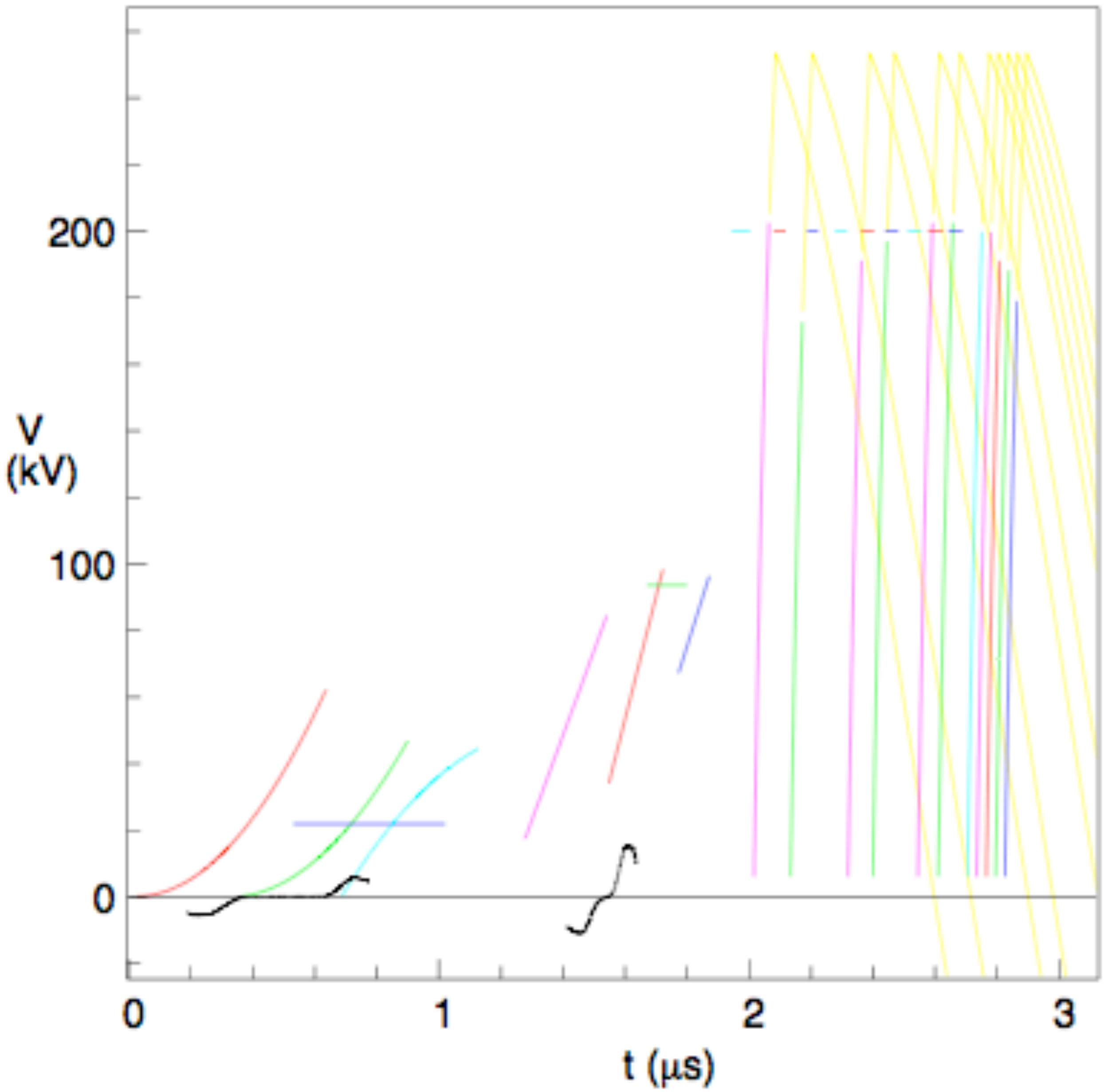
    For fringing gaps, no exact solution is possible; a least-squares optimization is used, penalizing both nonlinearlity and nonuniformity

Principle 2: Let It Bounce

- Rapid inward motion in beam frame is required to get below 70 ns
- Space charge ultimately inhibits this compression
- Beam is (ideally) nearly parabolic by this time
- However, this short a beam is not sustainable
  - Ears to confine it, much less apply a tilt, can't readily be made, especially with fringing gap fields
  - So, the beam "bounces" and starts to lengthen
- Fortunately, a longer beam still takes < 70 ns because it is now moving faster
- Allow it to lengthen while applying:
  - additional acceleration via flat pulses
  - confinement via ramped ("triangular") pulses
- Then use final gaps to apply the "exit tilt" needed for Neutralized Drift Compression

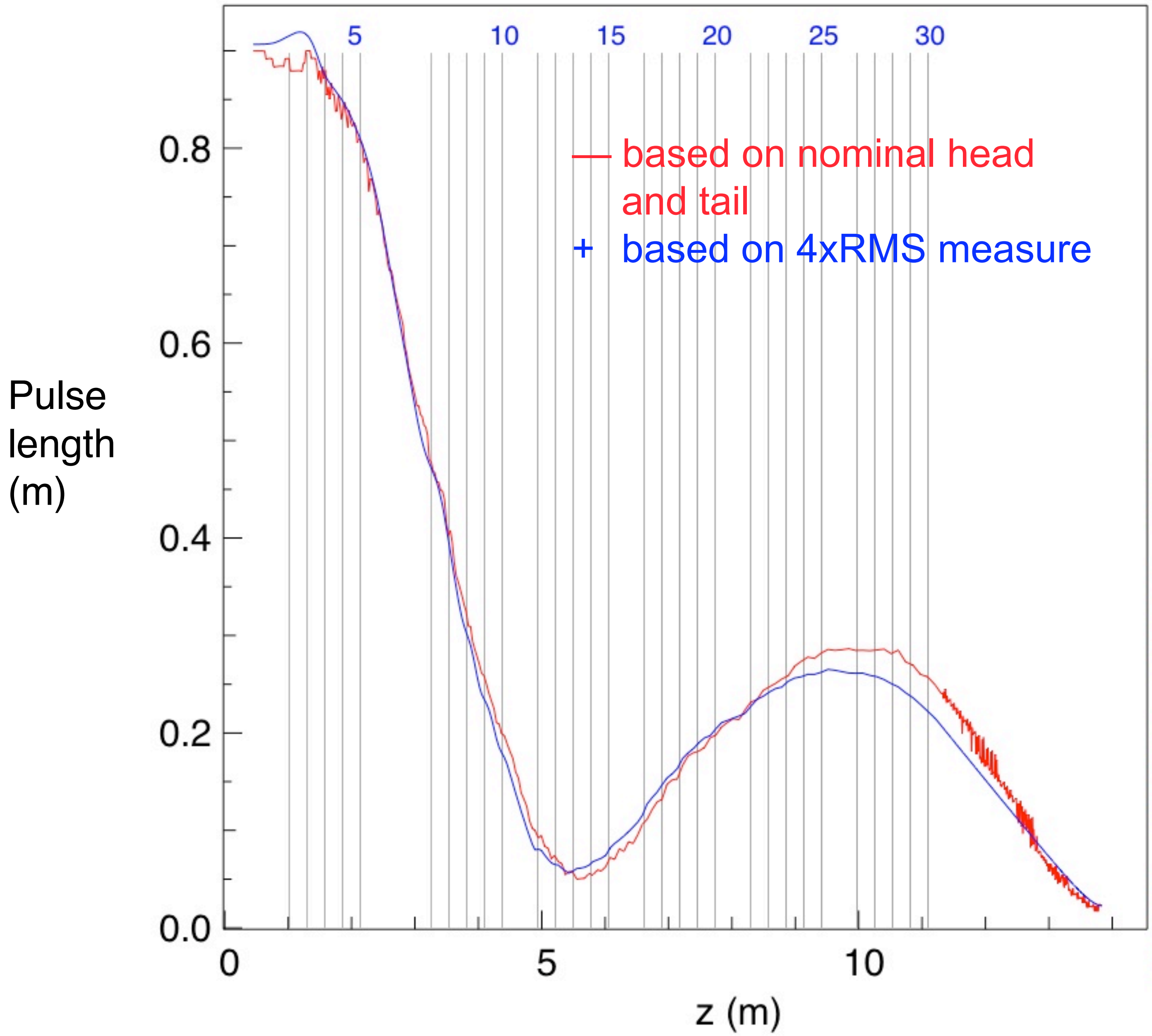
Design as developed using 1-D code

Voltage waveforms for all gaps

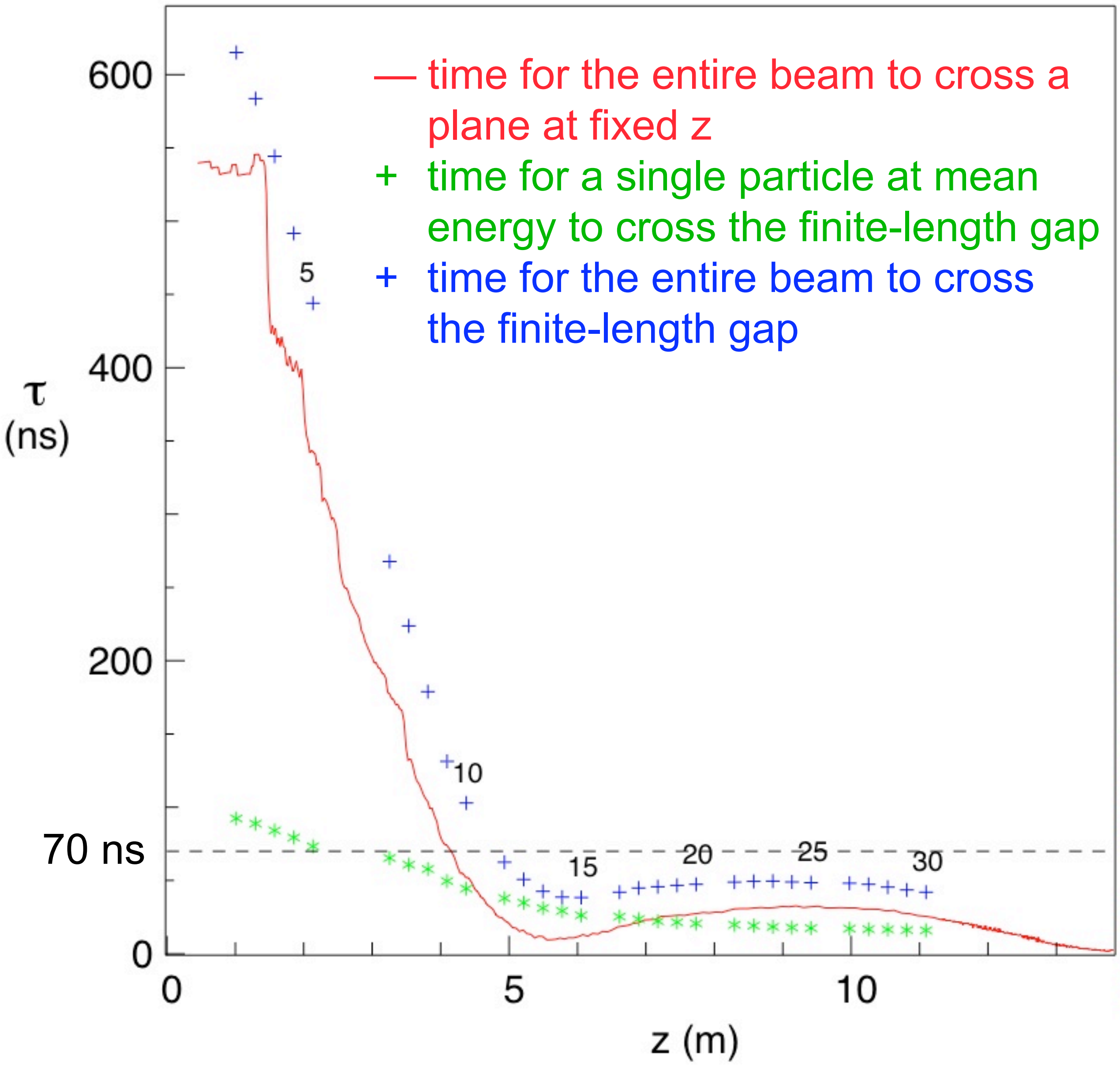


gap		gvr	gvd	gtdur
	trp:	rr2	cc2	
1		1000.00	-0.495	615.1
2		tbl		583.6
3		1000.00	-0.447	544.3
4		1.00	0.000	491.7
5		1000.00	0.305	444.0
6		5.00	0.000	267.7
7		tbl		223.8
8		3.00	0.000	178.8
9		1.00	0.000	131.3
10		1.50	0.000	102.8
11		1.00	0.000	62.5
12	trp	0.01	5.000	50.7
13		1.00	0.000	42.5
14	trp	0.01	5.000	38.6
15		1.00	0.000	38.4
16		1.00	0.000	41.9
17	trp	0.01	5.000	44.8
18		1.00	0.000	45.7
19	trp	0.01	5.000	46.7
20		1.00	0.000	47.3
21		1.00	0.000	48.9
22	trp	0.01	5.000	49.4
23		1.00	0.000	49.5
24	trp	0.01	5.000	49.0
25		1.00	0.000	48.5
26	trp	0.01	5.000	48.1
27	trp	0.01	5.000	47.3
28	trp	0.01	5.000	45.4
29	trp	0.01	5.000	43.5
30	trp	0.01	5.000	42.0

Pulse length (m) vs. z of center-of-mass

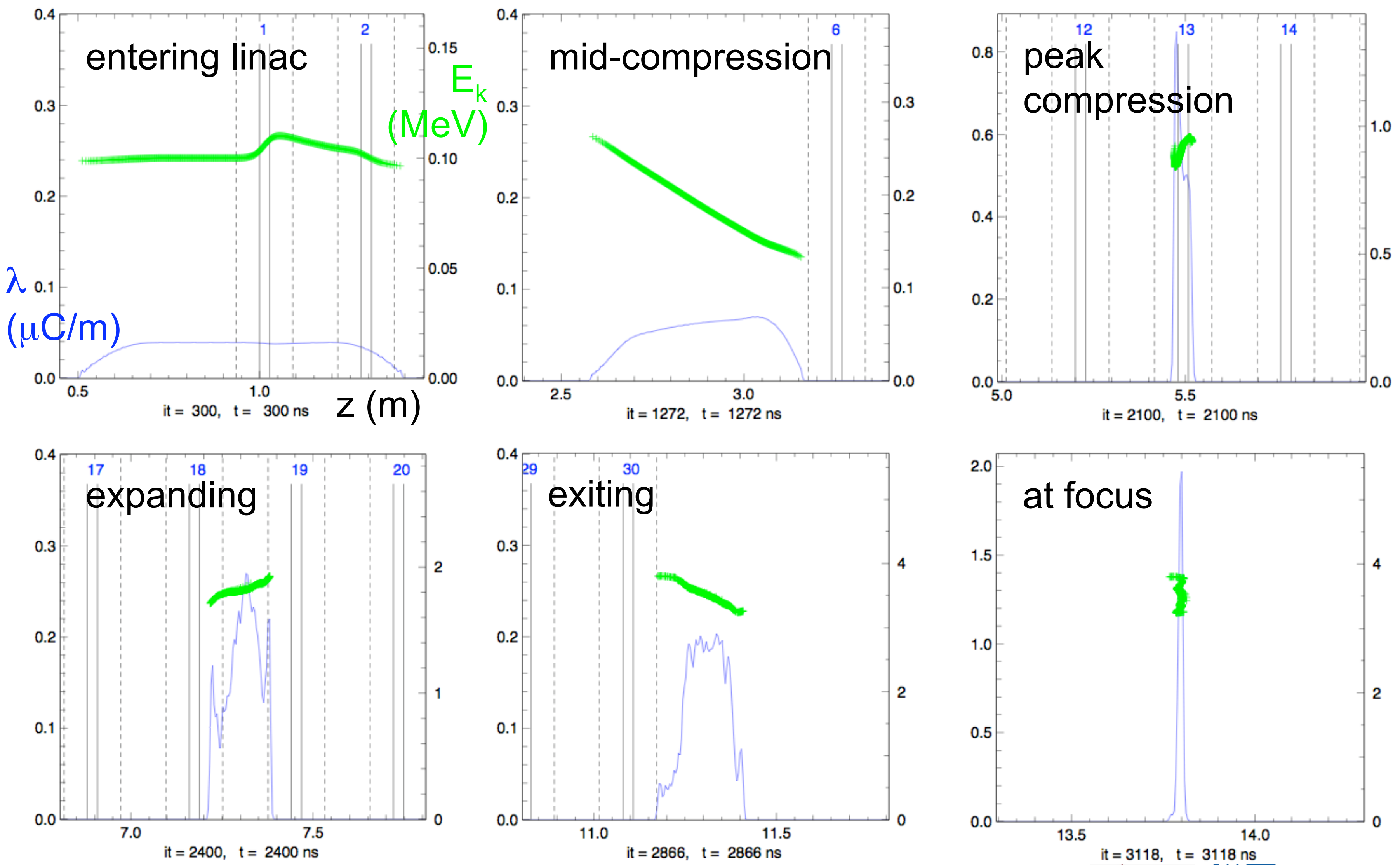


Pulse duration vs. z



gap	trp:	gvr rr2	gvd cc2	gtdur
1		1000.00	-0.495	615.1
2		tbl		583.6
3		1000.00	-0.447	544.3
4		1.00	0.000	491.7
5		1000.00	0.305	444.0
6		5.00	0.000	267.7
7		tbl		223.8
8		3.00	0.000	178.8
9		1.00	0.000	131.3
10		1.50	0.000	102.8
11		1.00	0.000	62.5
12	trp	0.01	5.000	50.7
13		1.00	0.000	42.5
14	trp	0.01	5.000	38.6
15		1.00	0.000	38.4
16		1.00	0.000	41.9
17	trp	0.01	5.000	44.8
18		1.00	0.000	45.7
19	trp	0.01	5.000	46.7
20		1.00	0.000	47.3
21		1.00	0.000	48.9
22	trp	0.01	5.000	49.4
23		1.00	0.000	49.5
24	trp	0.01	5.000	49.0
25		1.00	0.000	48.5
26	trp	0.01	5.000	48.1
27	trp	0.01	5.000	47.3
28	trp	0.01	5.000	45.4
29	trp	0.01	5.000	43.5
30	trp	0.01	5.000	42.0

A series of snapshots shows how the (E_k,z) phase space and the line charge density evolve



These snapshots show how the (v_z,z) phase space and the line charge density evolve (note the auto-scaling)

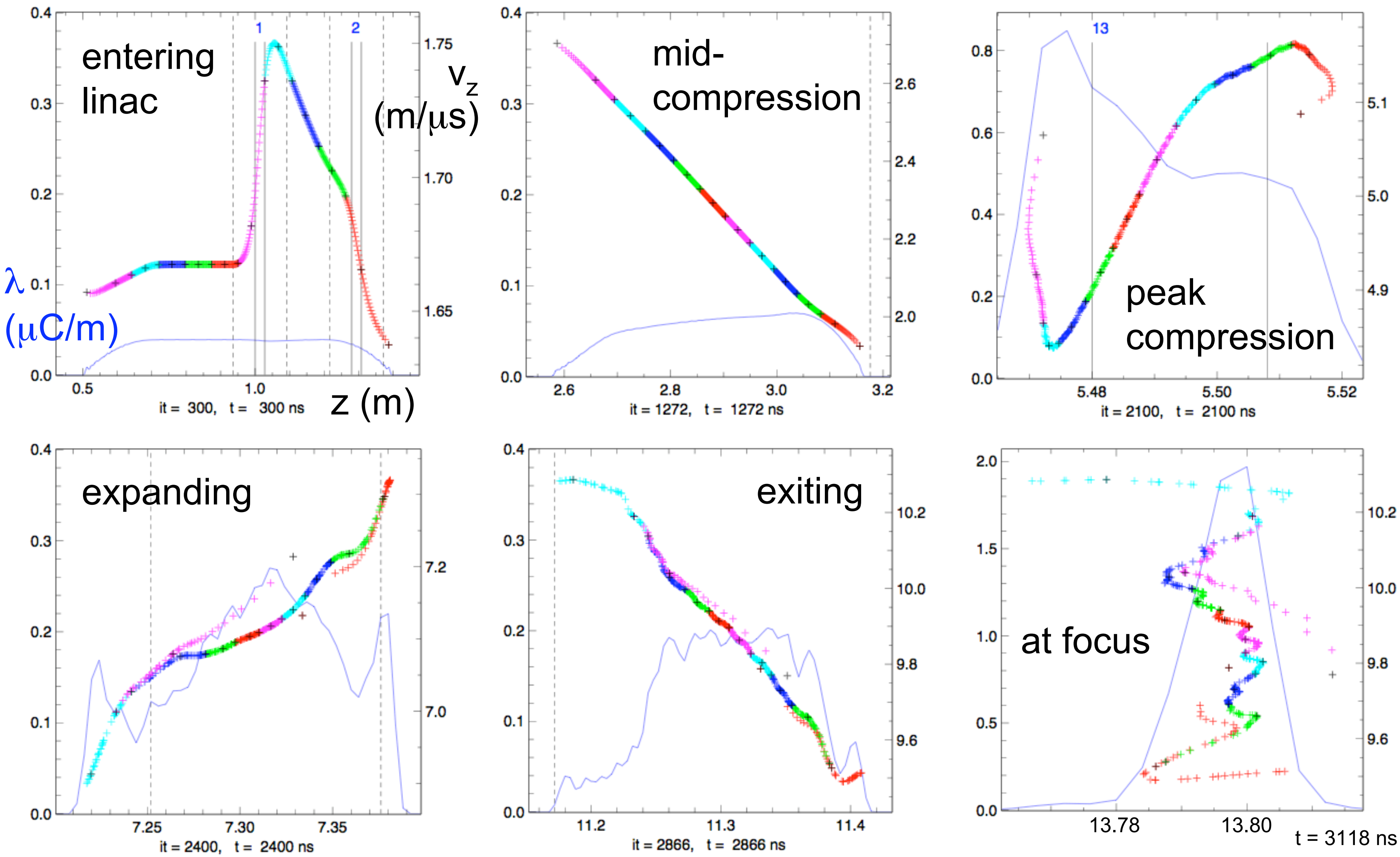
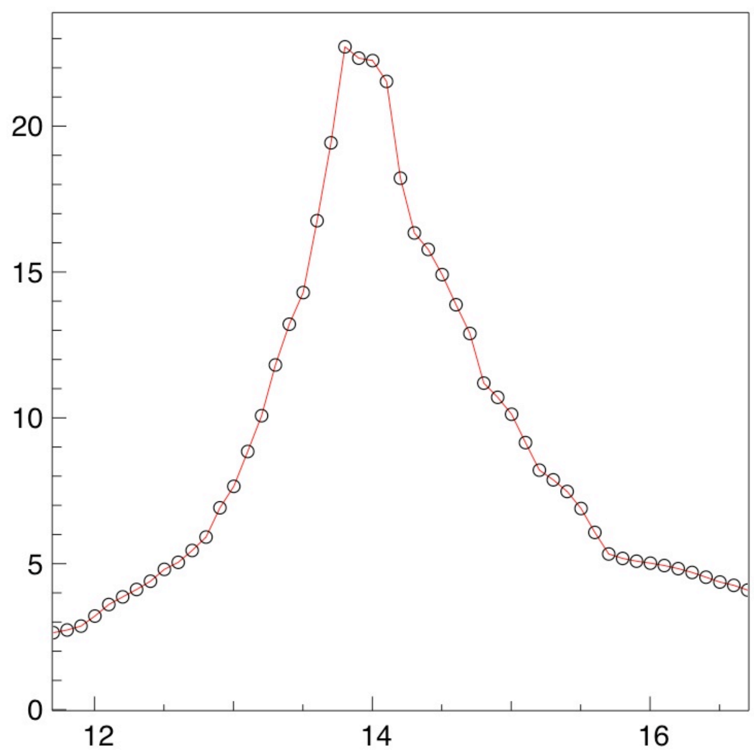


Figure-of-merit for longitudinal focus is motivated by target requirements for WDM studies

Focal plane is defined as: plane through which the greatest average beam current passes in a 1.0 ns window

Current (A) in optimal 1.0-ns window



z (m) of plane

Inputs to focus calc:

Bin duration 0.1 ns

Window duration 1.0 ns

Separation of trial planes 0.10 m

Results of focus calc:

RMS-estimated focal plane 14.2 m

'Best' focal plane 13.8 m

Average current in 1-ns window 22.7 A

Charge in window 22.7 nC

Percent of total charge in window 75.7 %

Average power in 1-ns window 79.8 MW

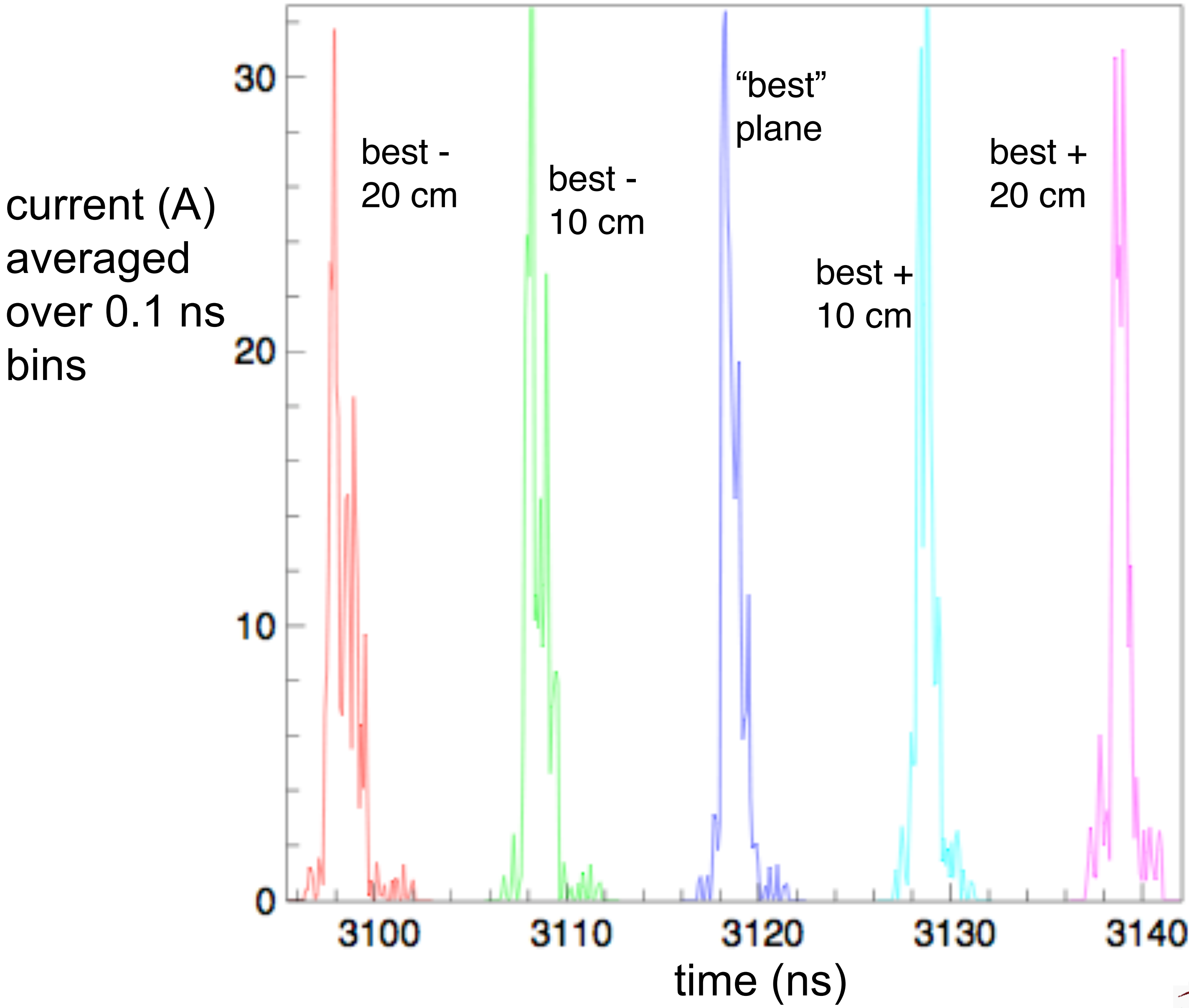
Energy in 1-ns window 79.8 mJ

Peak current at focal plane 32.4 A

Peak power at focal plane 113. 8 MW

FWHM at focal plane 0.99 ns

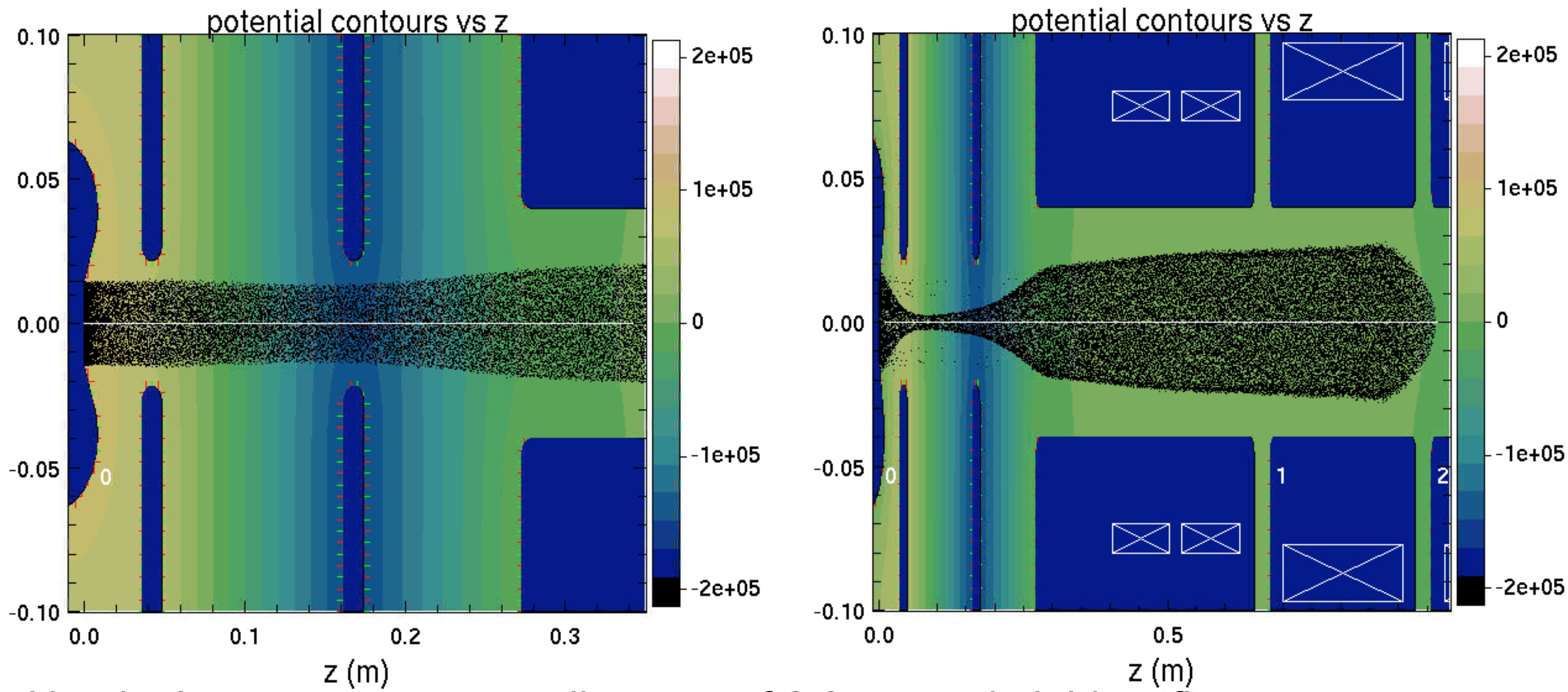
Longitudinal focus has a shallow optimum for this beam



Studies using Warp and LSP codes

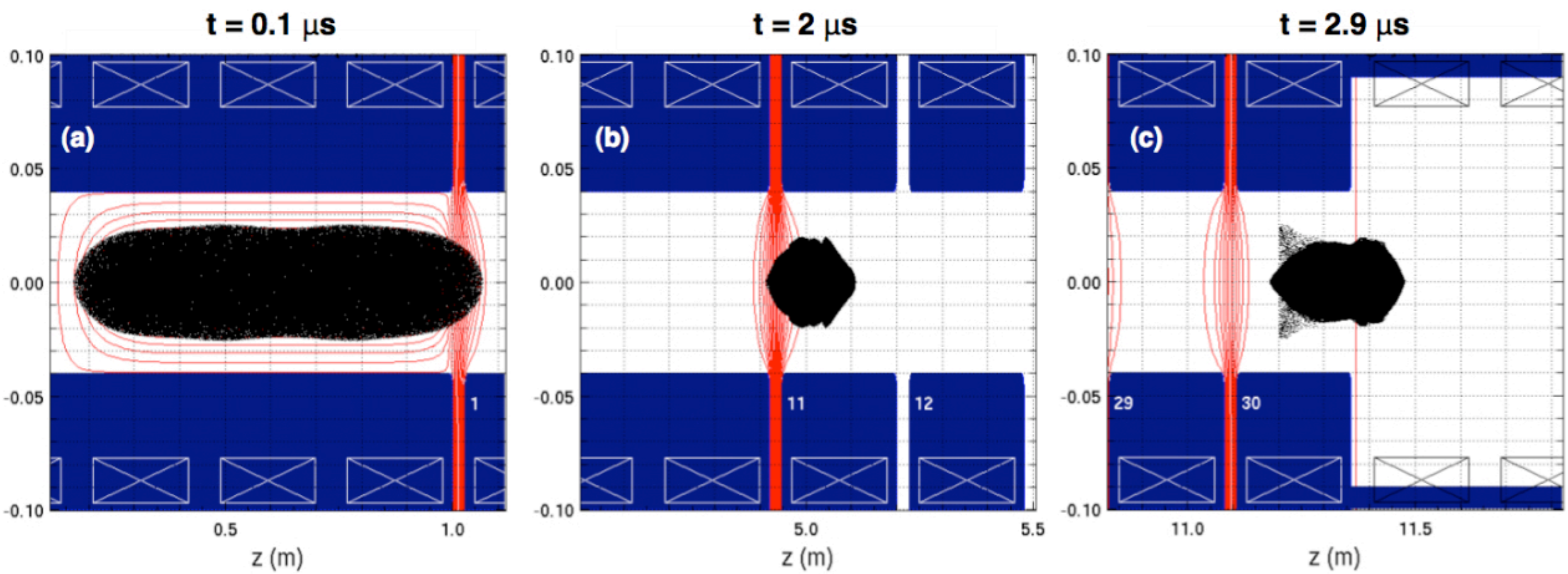
(see Bill Sharp poster)

Warp is used to simulate the accel-decel injection process



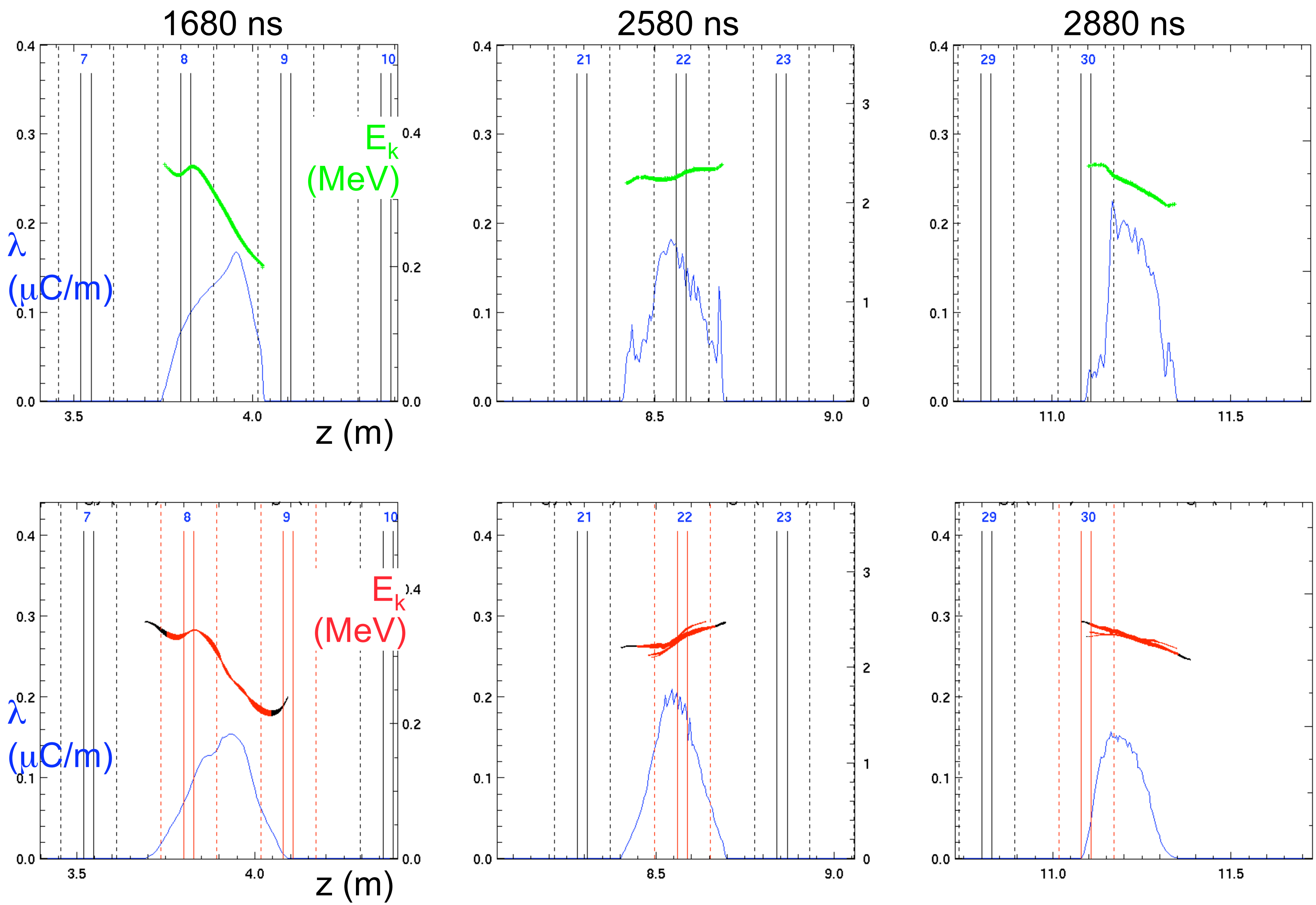
- Nominal run uses a source diameter of 2.9 cm and yields a flat-top current of 67 mA, giving 10.1 mA/cm^2.
- Could use a 1.4" (3.56 cm) source for 100 mA; would need to confirm that transverse confinement is adequate for “fatter” beam in “thinner” pipe.
- The flat-top energy at the first gap is 102 kV.
- The current rise time is ~ 40 ns; the emitter voltage rise time is ~ 110 ns.

Warp simulations show reasonably smooth transverse dynamics



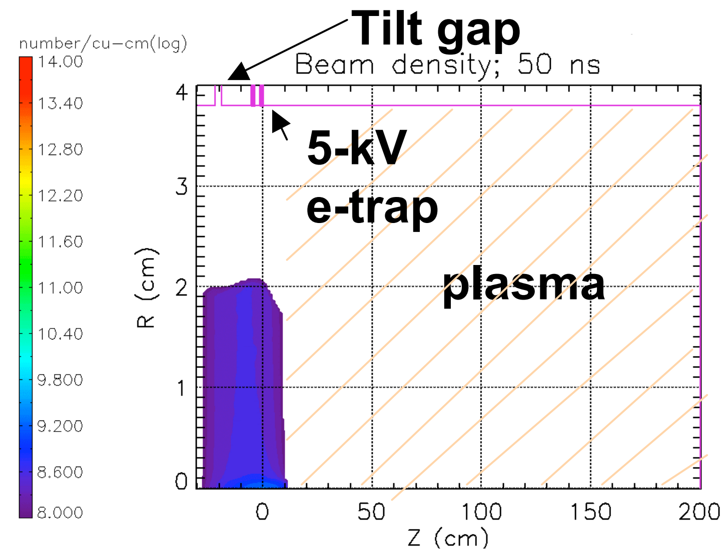
The normalized transverse emittance in this run grew in the accelerator from 0.9 to 1.2 mm-mr

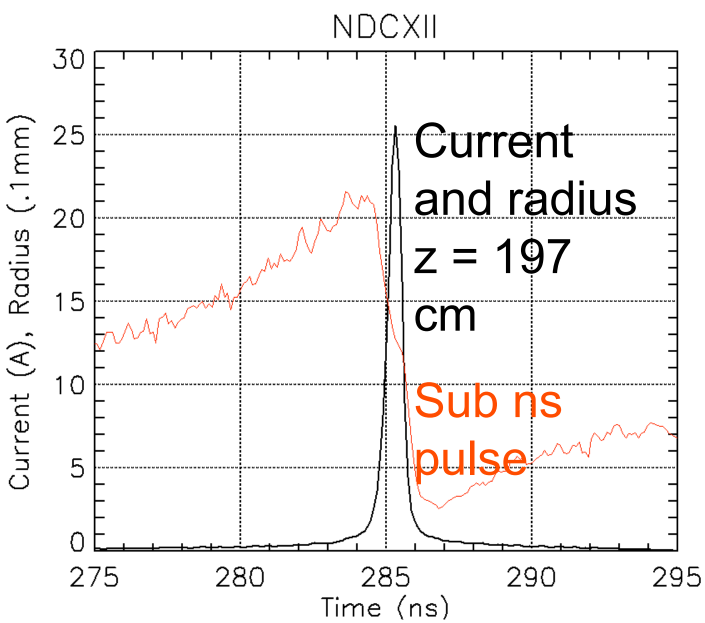
1-D code (top) & Warp (bottom) results agree, with differences

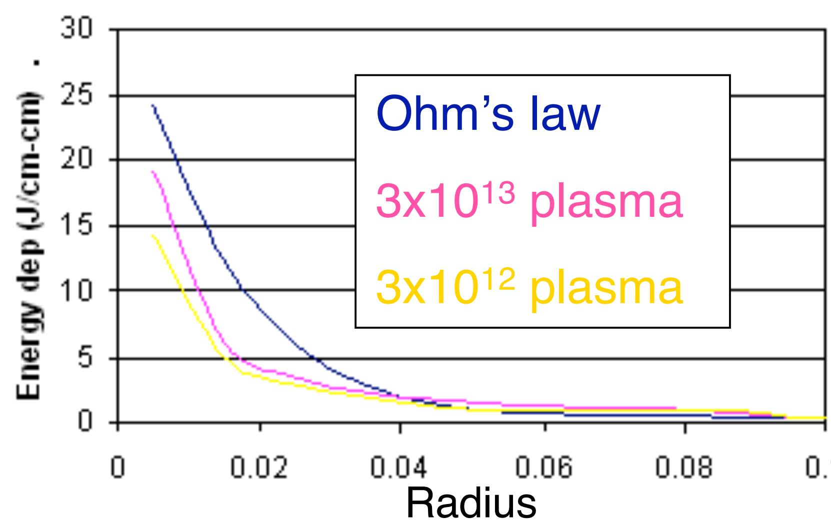


Simulations of NDCX-II neutralized compression and focus suggest that a plasma of density ~ 10^{14} cm^{-3} is desirable

- Idealized beam, uniform plasma, so far:
  - Li^+, 2.8 MeV, 1.67 eV temperature
  - 2-cm -5 or -6.7 mrad convergence
  - uniform current density; ε = 24 mm-mrad
  - 0.7-A with parabolic 50-ns profile
  - applying ideal tilt for 30 ns of beam
- ½ mm 1-ns beam has 2×10^{13} cm^{-3} density

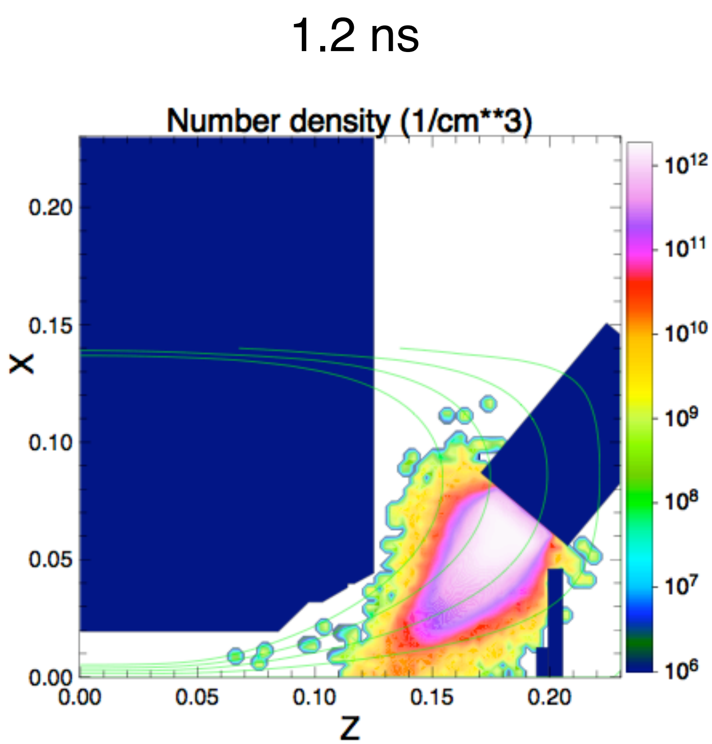


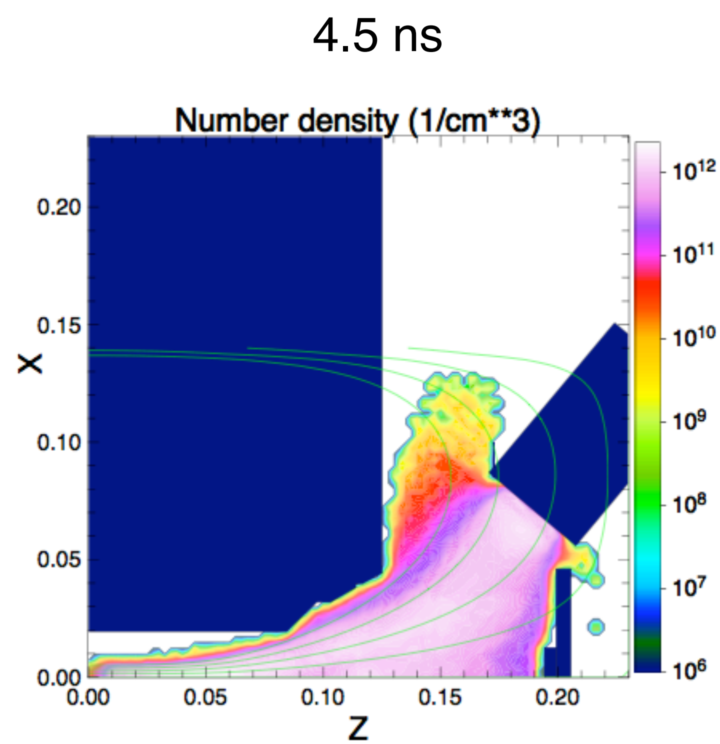




(LSP runs by D. Welch; others by A. Sefkow, M. Dorf; Warp code starting to be used)

We simulate injection from Cathodic-Arc Plasma sources





- This run corresponds to an NDCX-I configuration with 4 sources
- It was made by Dave Grote using Warp in 3-D mode
- LSP has been used extensively for such studies

Brief comment on PLIA

(see Chi Yeung Ling poster)

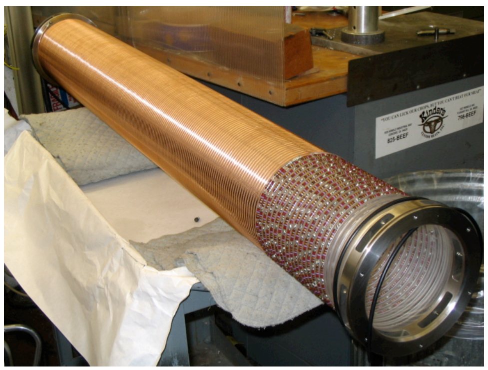
Pulse-Line Ion Accelerator (PLIA) may serve as a compact “afterburner” or an alternative front end

A traveling wave on a helical pulse line accelerates the ion bunch

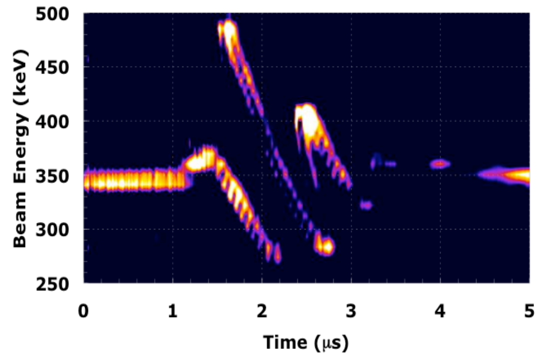
–“surfing” mode: acceleration of short bunch;

–“snowplow” mode: aceleration and bunching of long pulse

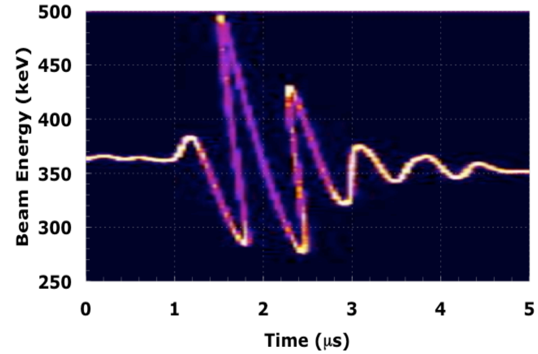
Proof-of-principle test on NDCX-I: acceleration & longitudinal bunching



Experiment

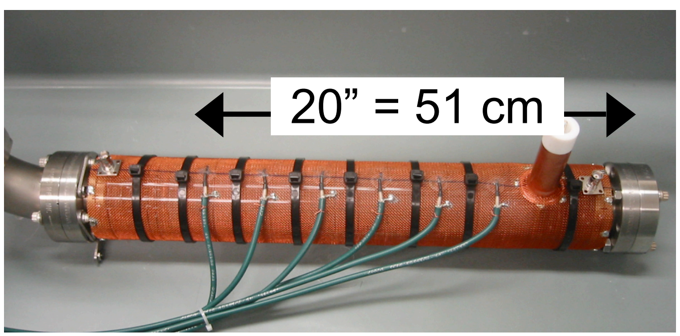


WARP Calculation



Voltage gradient was limited to < 0.2 MV/m by partial discharges in the vacuum

---



Scaled helix for high gradient testing

– so far, peak gradient 0.35 MV/m

– partial discharges traced to high frequency ringing from spark gap pulser, now reduced; further reduction is being pursued

What remains to be done

Progress has been encouraging; much remains to be done

- Proper accounting for initial beam-end energy variation due to space charge (the 1-D run shown was initiated with a fully-formed uniform-energy beam)
  - Other 1-D runs used a “model” initial energy variation and an entry “ear” cell; they produced compressed beams similar to the one shown
  - However, that variation was not realistic; a Warp run using the 1-D-derived waveforms yielded inferior compression
- Better understanding of beam-end wrap-around (causes and consequences)
- A prescription for setting solenoid strengths to yield a well-matched beam
- Optimized final focusing, accounting for dependence of the focal spot upon velocity tilt, focusing angle, and chromatic aberration
- Assessment of time-dependent focusing to correct for chromatic effects
- Development of plasma injection & control for neutralized compression & focusing (schemes other than the existing FCAPS may prove superior)
- Establishment of tolerances for waveforms and alignment

Major goals remain:

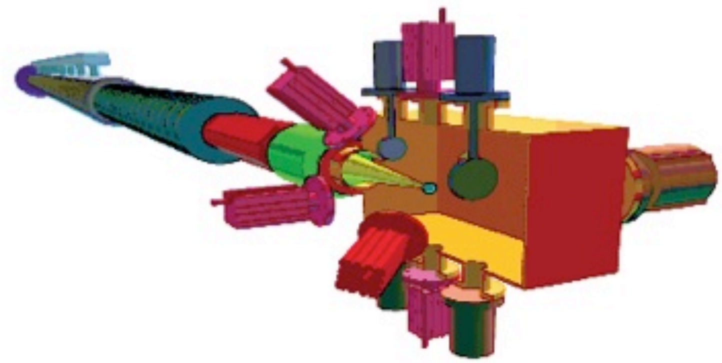
- a self-consistent source-through-target design, including assessment of tolerances etc., for WDM studies
- a prescription for modifications offering multiple pulses, ramped energy, and/or greater total energy, for ion direct drive studies

DOE priorities include an ion-driven Warm Dense Matter facility

From *An Interim Report on Facilities for the Future of Science* (August 2007):

Integrated Beam-High Energy Density Physics Experiment (IB-HEDPX)

Update: Mission Need for the IB-HEDPX (formerly called the Integrated Beam Experiment, or IBX), an intermediate-scale experiment using heavy ion beams for research on Warm Dense Matter (a midway state between solid matter and plasmas), was approved by the Department in 2005. Small-scale experiments are planned in 2008-2009 as part of R&D to provide a scientific basis for the new facility.



An IB-HEDPX capability for integrated acceleration compression and focusing on high current, space-charge-dominated beams would be unique—not available in any existing accelerator in the world.

From DOE's mission need document: "NDCX-II … is necessary R&D to assess the performance requirements of injection, acceleration and focusing of short pulses needed for the IB-HEDPX. Out of the $6M R&D cost (for IB-HEDPX), $5M is for hardware upgrade of NDCX-I to NDCX-II, which serves as a prototypical test-bed for the critical physics and engineering for developing the design and construction methodology of IB-HEDPX"